Finite temperature effects in antiferromagnetism of nuclear matter

A. A. Isayev
Kharkov Institute of Physics and Technology, Academicheskaya Str. 1, Kharkov, 61108, Ukraine
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The influence of the finite temperature on the antiferromagnetic (AFM) spin ordering in symmetric nuclear matter with the effective Gogny interaction is studied within the framework of a Fermi liquid formalism. It is shown that the AFM spin polarization parameter of partially polarized nuclear matter for low enough temperatures increases with temperature. The entropy of the AFM spin state for some temperature range is larger than the entropy of the normal state. Nerveless, the free energy of the AFM spin state is always less than the free energy of the normal state and, hence, the AFM spin polarized state is preferable for all temperatures below the critical temperature.

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INTRODUCTION

The spontaneous appearance of spin polarized states in nuclear matter is a topic of a great current interest due to its relevance in astrophysics. In particular, the effects of spin correlations in the medium strongly influence the neutrino cross section and neutrino mean free path. Therefore, depending on whether nuclear matter is spin polarized or not, drastically different scenarios of supernova explosion and cooling of neutron stars can be realized. Another aspect relates to pulsars, which are considered to be rapidly rotating neutron stars, surrounded by strong magnetic field. One of the hypotheses to explain such a strong magnetic field of a pulsar is that it can be produced by a spontaneous ordering of spins in the dense stellar core.

If a spin polarized state appears, nucleons with spin up and spin down lie on different Fermi surfaces. Spin-spin and spin-isospin correlations, leading to the formation of a spin polarized state, essentially depend on the overlap between Fermi surfaces. It is controlled by the number densities of nucleons of different species and spin polarization parameter, which, in turn, should be determined self-consistently.

From the general point of view, the problem of finding the phase diagram of a many-particle Fermi system when fermions lie on different Fermi surfaces is encountered in many physical cases. For example, thermodynamic properties of a neutron-proton condensate [1]–[6] in asymmetric nuclear matter are governed by pairing correlations between neutrons and protons, occupying two different Fermi spheres. Analogous situation appears in high density QCD, when the quark system is unstable against the formation of the $\langle q\, q\rangle$ color superconducting condensate [7]–[10]. Besides, one can mention the spin singlet pairing in a superconducting metal in the presence of magnetic impurities [11, 12] or the B-phase of the superfluid ^{3}He (Balian-Werthamer phase) in a magnetic field [13], when the spin degeneracy is loosened due to the Pauli paramagnetism. Another example is the appearance of BCS pairing in ultracold trapped quantum gases [14, 15, 16].

The possibility of a phase transition of normal neutron and nuclear matter to the ferromagnetic (FM) spin state was studied by many authors [17]–[26], predicting the ferromagnetic transition at $\varrho \approx (2–4)\varrho_0$ for different parametrizations of Skyrme forces ($\varrho_0 = 0.16\,\mathrm{fm}^{-3}$ is the nuclear matter saturation density). Competition between FM and AFM spin ordering in symmetric nuclear matter with the Skyrme effective interaction was studied in Ref. [27], where it was clarified that the FM spin state is thermodynamically preferable to the AFM one for all relevant densities. However, strongly asymmetric nuclear matter with Skyrme forces undergoes a phase transition to a state with oppositely directed spins of neutrons and protons [28]. The same conclusion in favour of antiparallel ordering of neutron and proton spins in symmetric nuclear matter was confirmed also in Ref. [29] for the Gogny effective interaction, where it was shown that the AFM spin state appears at $\varrho \approx 3.8\varrho_0$.

For the models with realistic nucleon-nucleon (NN) interaction, the ferromagnetic phase transition seems to be suppressed up to densities well above ϱ_0 [30]–[32]. In particular, no evidence of ferromagnetic instability has been found in recent studies of neutron matter [33] and asymmetric nuclear matter [34] within the Brueckner–Hartree–Fock approximation with realistic Nijmegen II, Reid93, and Nijmegen NSC97e NN interactions. The same conclusion was obtained in Ref. [35], where the magnetic susceptibility of neutron matter was calculated with the use of the Argonne v_{18} two–body potential and Urbana IX three–body potential.

Here we continue the study of spin polarized states in nuclear matter, using as a potential of NN interaction the effective Gogny forces [36, 37] and assuming that the AFM spin ordering is realized as a ground state of nuclear matter at zero temperature [29]. The main emphasis will be laid on determining the finite temperature behavior of the AFM spin polarization. The first goal of the study is to show that at low enough temperatures thermal fluctuations promote the AFM spin polarization of nuclear matter, when a system of nucleons can be treated as a

multicomponent Fermi liquid [38, 39, 40]. The second goal is to provide a fully self-consistent calculation of the basic thermodynamic functions of antiferromagnetically ordered nuclear matter at finite temperatures with a modern effective finite range NN interaction. In spite of that the entropy of the AFM spin state can be larger than the entropy of the normal state, the total balance of free energies lies with the AFM spin state for all temperatures below the critical temperature.

BASIC EQUATIONS

The normal states of nuclear matter are described by the normal distribution function of nucleons $f_{\kappa_1\kappa_2} = \mathrm{Tr}\,\varrho a^+_{\kappa_2} a_{\kappa_1}$, where $\kappa \equiv (\mathbf{p},\sigma,\tau)$, $\mathbf{p}$ is the momentum, $\sigma(\tau)$ is the projection of spin (isospin) on the third axis, and ϱ is the density matrix of the system. Bearing in mind to consider the possibility of FM and AFM phase transitions, the normal distribution function f and the nucleon single particle energy ε can be expanded in the Pauli matrices σ_i and τ_k in spin and isospin spaces

$$\begin{aligned} f(\mathbf{p}) &= f_{00}(\mathbf{p})\sigma_0\tau_0 + f_{30}(\mathbf{p})\sigma_3\tau_0 \qquad (1)\\ &\quad + f_{03}(\mathbf{p})\sigma_0\tau_3 + f_{33}(\mathbf{p})\sigma_3\tau_3. \\ \varepsilon(\mathbf{p}) &= \varepsilon_{00}(\mathbf{p})\sigma_0\tau_0 + \varepsilon_{30}(\mathbf{p})\sigma_3\tau_0 \qquad (2)\\ &\quad + \varepsilon_{03}(\mathbf{p})\sigma_0\tau_3 + \varepsilon_{33}(\mathbf{p})\sigma_3\tau_3. \end{aligned}$$

Expressions for the distribution functions $f_{00}, f_{30}, f_{03}, f_{33}$ in terms of the quantities ε read [27, 28]

$$\begin{aligned} f_{00} &= \frac{1}{4}\{n(\omega_{n\uparrow}) + n(\omega_{p\uparrow}) + n(\omega_{n\downarrow}) + n(\omega_{p\downarrow})\}, \\ f_{30} &= \frac{1}{4}\{n(\omega_{n\uparrow}) + n(\omega_{p\uparrow}) - n(\omega_{n\downarrow}) - n(\omega_{p\downarrow})\}, \qquad (3)\\ f_{03} &= \frac{1}{4}\{n(\omega_{n\uparrow}) - n(\omega_{p\uparrow}) + n(\omega_{n\downarrow}) - n(\omega_{p\downarrow})\}, \\ f_{33} &= \frac{1}{4}\{n(\omega_{n\uparrow}) - n(\omega_{p\uparrow}) - n(\omega_{n\downarrow}) + n(\omega_{p\downarrow})\}. \end{aligned}$$

Here $n(\omega) = \{\exp(\omega/T) + 1\}^{-1}$ and

$$\begin{aligned} \omega_{n\uparrow} &= \xi_{00} + \xi_{30} + \xi_{03} + \xi_{33}, \\ \omega_{p\uparrow} &= \xi_{00} + \xi_{30} - \xi_{03} - \xi_{33}, \qquad (4)\\ \omega_{n\downarrow} &= \xi_{00} - \xi_{30} + \xi_{03} - \xi_{33}, \\ \omega_{p\downarrow} &= \xi_{00} - \xi_{30} - \xi_{03} + \xi_{33}, \end{aligned}$$

where

$$\begin{aligned} &\xi_{00} = \varepsilon_{00} - \mu_{00},\ \xi_{30} = \varepsilon_{30}, \\ &\xi_{03} = \varepsilon_{03} - \mu_{03},\ \xi_{33} = \varepsilon_{33}, \\ &\mu_{00} = \frac{\mu_n + \mu_p}{2}, \quad \mu_{03} = \frac{\mu_n - \mu_p}{2}. \end{aligned}$$

μ_n, μ_p being the chemical potentials of neutrons and protons. The branches $\omega_{n\uparrow}, \omega_{n\downarrow}$ of the quasiparticle spectrum correspond to neutrons with spin up and spin down, and the branches $\omega_{p\uparrow}, \omega_{p\downarrow}$ correspond to protons with spin up and spin down.

The distribution functions f should satisfy the normalization conditions

$$\frac{4}{\mathcal{V}}\sum_{\mathbf{p}} f_{00}(\mathbf{p}) = \varrho, \qquad (5)$$

$$\frac{4}{\mathcal{V}}\sum_{\mathbf{p}} f_{03}(\mathbf{p}) = \varrho_n - \varrho_p \equiv \alpha\varrho, \qquad (6)$$

$$\frac{4}{\mathcal{V}}\sum_{\mathbf{p}} f_{30}(\mathbf{p}) = \varrho_\uparrow - \varrho_\downarrow \equiv \Delta\varrho_{\uparrow\uparrow}, \qquad (7)$$

$$\frac{4}{\mathcal{V}}\sum_{\mathbf{p}} f_{33}(\mathbf{p}) = (\varrho_{n\uparrow} + \varrho_{p\downarrow}) - (\varrho_{n\downarrow} + \varrho_{p\uparrow}) \equiv \Delta\varrho_{\uparrow\downarrow}. \qquad (8)$$

Here α is the isospin asymmetry parameter, $\varrho_{n\uparrow}, \varrho_{n\downarrow}$ and $\varrho_{p\uparrow}, \varrho_{p\downarrow}$ are the neutron and proton number densities with spin up and spin down, respectively; $\varrho_\uparrow = \varrho_{n\uparrow} + \varrho_{p\uparrow}$ and $\varrho_\downarrow = \varrho_{n\downarrow} + \varrho_{p\downarrow}$ are the nucleon densities with spin up and spin down. The quantities $\Delta\varrho_{\uparrow\uparrow}$ and $\Delta\varrho_{\uparrow\downarrow}$ play the roles of FM and AFM spin order parameters [28].

The self–consistent equations for the components of the single particle energy have the form [27, 28]

$$\begin{aligned} &\xi_{00}(\mathbf{p}) = \varepsilon_0(\mathbf{p}) + \tilde\varepsilon_{00}(\mathbf{p}) - \mu_{00},\ \xi_{30}(\mathbf{p}) = \tilde\varepsilon_{30}(\mathbf{p}), \qquad (9)\\ &\xi_{03}(\mathbf{p}) = \tilde\varepsilon_{03}(\mathbf{p}) - \mu_{03},\ \xi_{33}(\mathbf{p}) = \tilde\varepsilon_{33}(\mathbf{p}). \end{aligned}$$

Here $\varepsilon_0(\mathbf{p})$ is the free single particle spectrum, and $\tilde\varepsilon_{00}, \tilde\varepsilon_{30}, \tilde\varepsilon_{03}, \tilde\varepsilon_{33}$ are the FL corrections to the free single particle spectrum, related to the normal FL amplitudes $U_0(\mathbf{k}), ..., U_3(\mathbf{k})$ by formulas

$$\begin{aligned} \tilde\varepsilon_{00}(\mathbf{p}) &= \frac{1}{2\mathcal{V}}\sum_{\mathbf{q}} U_0(\mathbf{k}) f_{00}(\mathbf{q}),\ \mathbf{k} = \frac{\mathbf{p}-\mathbf{q}}{2}, \qquad (10)\\ \tilde\varepsilon_{30}(\mathbf{p}) &= \frac{1}{2\mathcal{V}}\sum_{\mathbf{q}} U_1(\mathbf{k}) f_{30}(\mathbf{q}), \\ \tilde\varepsilon_{03}(\mathbf{p}) &= \frac{1}{2\mathcal{V}}\sum_{\mathbf{q}} U_2(\mathbf{k}) f_{03}(\mathbf{q}), \\ \tilde\varepsilon_{33}(\mathbf{p}) &= \frac{1}{2\mathcal{V}}\sum_{\mathbf{q}} U_3(\mathbf{k}) f_{33}(\mathbf{q}). \end{aligned}$$

To obtain numerical results, we use the effective Gogny interaction D1S [37]. Expressions for the normal FL amplitudes in terms of Gogny force parameters were written in Ref. [29]. Thus, with account of expressions (3) for the distribution functions f, we obtain the self–consistent equations (9), (10) for the components of the single particle energy $\xi_{00}(\mathbf{p}), \xi_{30}(\mathbf{p}), \xi_{03}(\mathbf{p}), \xi_{33}(\mathbf{p})$, which should be solved jointly with the normalization conditions (5)–(8), determining the chemical potentials μ_{00}, μ_{03}, FM and AFM spin order parameters $\Delta\varrho_{\uparrow\uparrow}$, $\Delta\varrho_{\uparrow\downarrow}$.

To examine the thermodynamic stability of different solutions of self-consistent equations, it is necessary to compare the corresponding free energies $F = E - TS$,

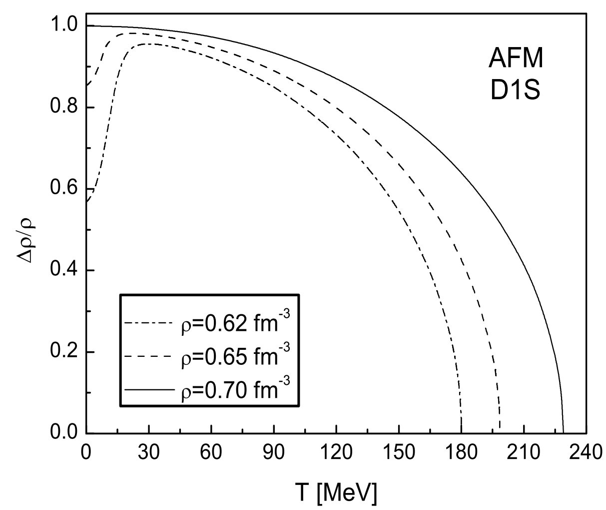

FIG. 1: AFM spin polarization parameter as a function of temperature at different densities for the D1S Gogny force.

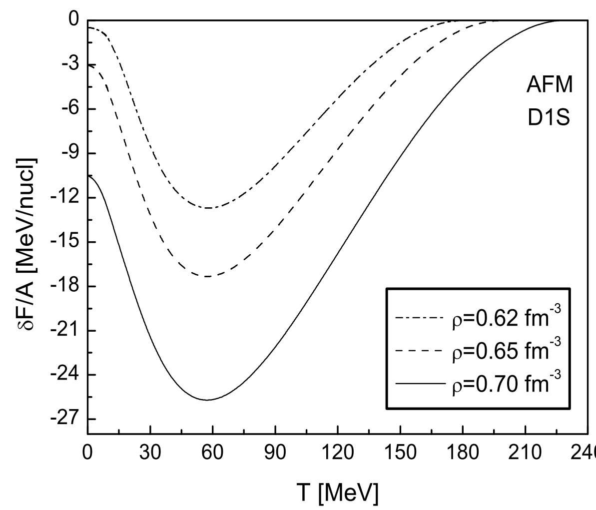

FIG. 2: The free energy per nucleon, measured from its value in the normal state, for the AFM spin state as a function of temperature at different densities for the D1S Gogny force.

where the energy functional E is characterized, in the general case, by four FL amplitudes $U_0, ..., U_3$ and the entropy reads

$$S = -\sum_{\mathbf{p}} \sum_{\tau=n,\,p} \sum_{\sigma=\uparrow,\,\downarrow} \{n(\omega_{\tau\sigma}) \ln n(\omega_{\tau\sigma}) + \bar{n}(\omega_{\tau\sigma}) \ln \bar{n}(\omega_{\tau\sigma})\},\ \bar{n}(\omega) = 1 - n(\omega).$$

PHASE TRANSITIONS AT FINITE TEMPERATURE

Further we will consider symmetric nuclear matter ($\varrho_n = \varrho_p$). It was shown in Ref. [29] that in symmetric nuclear matter with D1S Gogny interaction only the AFM spin ordering is realized at zero temperature, but the self–consistent equations have no solutions at all corresponding to the FM spin ordering. Our aim here is to study the temperature behavior of the AFM spin polarization in the whole temperature domain below the critical temperature, $T \leq T_c$.

In the AFM spin state of symmetric nuclear matter $\varrho_{n\uparrow} = \varrho_{p\downarrow}, \varrho_{n\downarrow} = \varrho_{p\uparrow}$, neutrons with spin up and protons with spin down fill the Fermi surface of radius k_2 and neutrons with spin down and protons with spin up occupy the Fermi surface of radius k_1, satisfying at zero temperature the equations

$$\frac{1}{3\pi^2}(k_2^3 - k_1^3) = \Delta\varrho_{\uparrow\downarrow}, \quad \frac{1}{3\pi^2}(k_1^3 + k_2^3) = \varrho.$$

Now we present the results of the numerical solution of the self–consistent equations with the D1S Gogny effective force. In Fig. 1 it is shown the dependence of the AFM spin polarization parameter $\Delta\varrho_{\uparrow\downarrow}/\varrho$ as a function of temperature at different fixed densities. The interesting feature is that, if at $T = 0$ we have partially AFM polarized state ($\Delta\varrho_{\uparrow\downarrow}/\varrho < 1$), then under increase of temperature within some temperature interval the AFM spin polarization parameter increases as well. This behavior is in contrast with the intuitive supposition that thermal fluctuations act as a destroying factor on spin ordering. Oppositely, for not too large temperatures thermal fluctuations in nuclear matter promote the AFM spin ordering. The reason for such a behavior is that thermal fluctuations smear Fermi surfaces of nucleons, leading, thus, to increasing overlap between Fermi surfaces. Since interaction between free nucleons is most strong between a neutron and a proton in the spin triplet state, then, mainly, due to this interaction, modified by the medium, some of neutrons with spin down and protons with spin up undergo spin flip transitions from the inner Fermi surface to the outer one. Thus, initial increase of AFM spin polarization with temperature is a result of influence of thermal effects and medium correlations. Under further increasing temperature thermal fluctuations suppress AFM spin ordering, until it completely vanishes.

In Fig. 2, the difference between the free energies per nucleon of the spin ordered and normal states is shown as a function of temperature for different fixed densities. One can see that, first, as a result of the initial increase of AFM spin polarization, the free energy of the AFM spin state decreases with temperature and after that the difference between the free energies of the AFM and normal states becomes smaller, until it vanishes at critical temperature, dependent on density.

Unexpected moment appears if we consider separately the temperature behavior of the entropy of the AFM state. In Fig. 3, the difference between the densities of

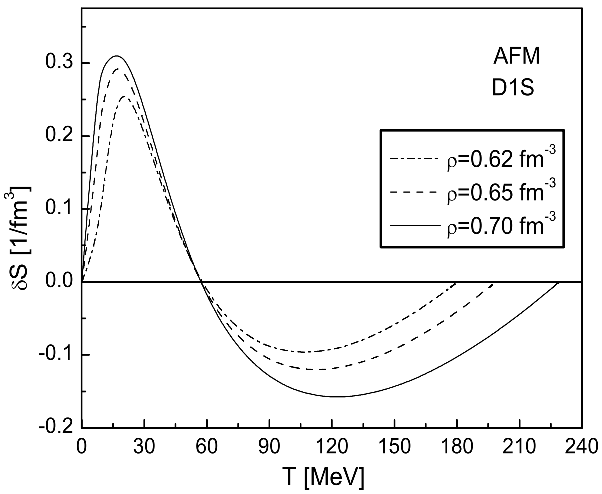

FIG. 3: Same as in Fig. 2, but for the density of entropy, measured from its value in the normal state.

the entropies of the AFM and normal states is shown as a function of temperature. One can see that for low temperatures the entropy of the AFM state is larger than the entropy of the normal state. It looks like the AFM state at low finite temperatures is less ordered than the normal state. Under further increasing temperature the difference of the entropies changes its sign and becomes negative, that corresponds to the intuitively expected behavior. In spite of that the entropy of the AFM state may be larger or less than the entropy of the normal state, the difference of the free energies preserves its sign for all temperatures below T_c. Note that analogous anomalous behavior of the entropy with temperature was observed also in superfluid asymmetric nuclear matter [5]. In that case for low enough temperatures the entropy of the superfluid state is larger than that for the normal state. Nerveless, as in our case, the total balance of the free energies is preserved in favour of superfluid state for all temperatures below the critical temperature. It is worthy to note that for the AFM spin state anomalous behavior of the entropy is observed already in symmetric nuclear matter while in the superfluid case it is observed only at finite isospin asymmetry. The difference is that in the spin ordered state the separation of Fermi surfaces is controlled by the AFM spin polarization parameter which, in turn, is not an independent quantity, but should be found self-consistently.

Note that the stability of the equation of state of nuclear matter with the Skyrme effective interaction in terms of Landau parameters was examined in Ref. [41], where the stability conditions were formulated as the inequalities for the Skyrme force parameters. This study is based on the approximation of the effective mass, when the quadratic terms on momentum in the Skyrme interaction are incorporated in the single particle spectrum. The approximation of the effective mass, being independent of temperature as in Ref. [41], is a strong simplifying assumption and cannot explain the change in the sign of the difference between entropies of polarized and unpolarized states at certain temperature, as seen from Fig. 3. In the general case of a finite range interaction, like Gogny force in our case or Paris NN potential in Ref. [5], the single particle spectrum is to be determined self-consistently by solving the corresponding integral equations (in our case, Eqs. (10)). Thus, the anomalous behavior of the entropy with temperature should be associated with the complicated renormalization of the free single particle spectrum in a strongly interacting nucleon medium.

Note that, since in the present study only symmetric nuclear matter has been considered, the obtained results cannot be directly extrapolated to proto-neutron stars, whose core represents essentially asymmetric nuclear matter. For strongly isospin asymmetric system, the appropriate choice of the Gogny force is the use of the D1P parametrization [42], giving the correct behavior of the energy per nucleon at high densities.

In summary, we have considered AFM polarized states in symmetric nuclear matter with the effective Gogny interaction at finite temperatures. It has been shown that the AFM spin polarization initially increases with temperature as a result of smearing Fermi surfaces of nucleons due to thermal fluctuations and spin and isospin dependent correlations in the medium. While the difference of the entropies of the AFM and normal states anomalously changes its sign at certain temperature, the total balance of the free energies lies with the AFM spin state for all temperatures below the critical temperature.

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